

Chapter 9

Formation Channels for Blue Straggler Stars

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9.1 Introduction

As has been discussed earlier in this book, blue stragglers sit on the main sequence but above the current turn-off mass. Their existence is at first surprising: one would have expected these stars to have evolved off the main sequence and become white dwarfs some time ago. How could a subset of stars somehow forget to evolve off the main sequence? In this chapter, we will focus on two, distinct, alternatives for blue straggler production: direct collisions between two stars (leading to their merger), and mass transfer (or merger) between two stars as part of natural evolution within a binary system. We will see that both formation mechanisms probably occur, at least in some clusters. One should also note that stellar mergers can occur also in triples as the inner binary is driven into contact by the action of the third star via the Kozai effect [29]. This pathway is discussed in detail in Chap. 11.

We begin by outlining some of the key concepts and ideas which will be discussed in more detail in later sections of this chapter:

a) Stellar collisions occur often in the cores of dense stellar clusters

Physical collisions between stars occur interestingly-often in the cores of the densest star clusters. Most of the collisions occur whilst the stars are on the main sequence. Because the relative speed of the stars within stellar clusters is much smaller than their surface escape speeds, collisions between two main sequence stars will lead to their merger with only a very small amount of mass loss.

b) The post-collision evolution of merger products is complex

The post-collision evolution of merger products is complex, with many uncertainties. Merger products typically contain a relatively large amount of angular momentum. In other words, the stars will be rotating sufficiently rapidly that they may be significantly non-spherical. Mixing within the merger product is critical

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when one considers the refueling of the core with unburned hydrogen and thus calculations of the lifetime of the merger product.

c) Encounters involving binary stars can be as frequent as those involving only single stars

A binary poses a much larger target for encounters than single stars. Thus even if only a small fraction of stars are contained in binaries, the event rate for strong encounters between binaries and single stars can be comparable to (or possibly even in some cases exceed) the event rate for encounters between two single stars. Stellar collisions will occur in a subset of encounters involving binaries thus potentially producing blue stragglers. Stellar collisions occurring during encounters between two binaries will be important in less-dense clusters.

d) Blue stragglers may also be produced through the natural evolution of isolated binaries

In the case of very tight binaries, angular momentum loss via winds may drive the two stars together forming a merger product not very different from that formed via collisional mergers. Alternatively when the primary star evolves, it may fill its Roche lobe and transfer mass on to the secondary star. If the mass transfer is stable, this may add sufficient mass to the secondary to convert it into a blue straggler.

e) The observed blue straggler population is probably a combination of those formed via mergers and those formed from the evolution of binaries

Blue stragglers can be formed either via mergers (as the outcome of collisions) or via mass transfer (or merger) as an outcome of isolated-binary evolution. We will see that a combination of both formation channels probably occurs in most globular clusters, whilst binary evolution is most likely to be more important in less-dense clusters such as open clusters, and in the halo.

This chapter is arranged as follows. In Sec. 9.2, we review stellar collisions considering the collision rate within clusters, which types of stars are likely to be involved in collisions, and their immediate outcome. We review the post-collision evolution of merger products in Sec. 9.3. In Sec. 9.4, we describe encounters between binary star systems and single stars or other binaries. The evolution of isolated binaries is dealt with in Sec. 9.5, where we consider the effect of mass transfer on enhancing the mass of the secondary star, potentially converting it into a blue straggler. In Sec. 9.6 we consider the blue straggler population which may be produced as a combination of those formed via collisions and those formed via mass transfer as part of the evolution of binaries.

9.2 Stellar Collisions

In order for collisions to contribute significantly to the observed blue straggler population, we need a number of conditions to be satisfied: 1) collisions must occur at interesting rates within stellar clusters; 2) collisions must lead to the merger of stars; 3) the merger product must look like a moderately-massive main sequence

star (i.e. consistent with observations); and 4) the merger products must have a sufficiently long lifetime to produce a sufficiently large population of blue stragglers. We consider points 1) and 2) in this section, and points 3) and 4) in Sec. 9.3.

We begin by calculating the stellar encounter rate within clusters. The cross section for two stars, having a relative velocity at infinity of V_∞ , to pass within a distance R_{\min} is given by

$$\sigma = \pi R_{\min}^2 \left(1 + \frac{V^2}{V_\infty^2} \right), \quad (9.1)$$

where V is the relative velocity of the two stars at closest approach in a parabolic encounter (*i.e.* $V^2 = 2G(M_1 + M_2)/R_{\min}$, where M_1 and M_2 are the masses of the two stars). The second term is due to the attractive gravitational force, and is referred to as gravitational focussing. In the regime where $V \ll V_\infty$ (as might be the case in galactic nuclei with extremely high velocity dispersions), we recover the result, $\sigma \propto R_{\min}^2$. However, if $V \gg V_\infty$ as will be the case in systems with low velocity dispersions, such as globular and open clusters, $\sigma \propto R_{\min}$. This will have consequences for the relative frequency of collisions at various stages of stellar evolution as will see below.

One may estimate the timescale for a given star to undergo an encounter with another star, $\tau_{\text{coll}} = 1/n\sigma v$. For clusters with low velocity dispersions, we thus obtain

$$\tau_{\text{coll}} \simeq 10^{11} \text{yr} \left(\frac{10^5 \text{pc}^{-3}}{n} \right) \left(\frac{V_\infty}{10 \text{km/s}} \right) \left(\frac{R_\odot}{R_{\min}} \right) \left(\frac{M_\odot}{M} \right), \quad (9.2)$$

where n is the number density of single stars of mass M . For an encounter between two single stars to be hydrodynamically interesting, we typically require $R_{\min} \sim 3R_\star$ for $V_\infty = 10 \text{ km/s}$ (see for example, [5]). We thus see that for typical globular clusters, where $n \sim 10^5 \text{ stars/pc}^3$, up to 10% of the stars in the cluster cores will have undergone a collision at some point during the lifetime of the cluster.

Stars spend a large fraction of their life on the main sequence, where helium is produced through fusion of hydrogen within their cores. Once the hydrogen fuel is exhausted, stars then evolve off the main sequence and move towards the red giant branch where hydrogen fusion reactions occur in a shell above a contracting helium core, as the surrounding envelope expands to about $100 R_\odot$. For low-mass stars, once helium ignition occurs within the core, the star shrinks to about $10 R_\odot$ as it stays on the horizontal branch, fusing helium into carbon in its core. Post-horizontal branch, the star evolves up the asymptotic giant branch, expanding to length scales of around $300 R_\odot$. Low-mass stars then eject their envelopes producing a white dwarf, whilst stars more massive than $8 M_\odot$ will explode as a core-collapse supernova, leaving either a neutron star or (for the most massive stars) a stellar mass black hole (see Chap. 1 for a more detailed discussion).

It is possible for stars to be involved in collisions during all of the phases of stellar evolution described above, as shown in Fig. 9.1. Of interest to us here are the collisions involving two main sequence stars which may produce at least some of the observed blue stragglers.

Fig. 9.1 Plot showing the grid of possible collisions between various stellar species: main sequence stars (MS), red giants (RG), white dwarfs (WD) and neutron stars (NS). Collisions between two main sequence stars may produce at least some of the observed blue stragglers (BS). Collisions between either main sequence stars or red giants and white dwarfs or neutron stars may produce interacting binaries (cataclysmic variables and low-mass X-ray binaries). Encounters involving two neutron stars could potentially produce gamma-ray bursts (GRB).

	MS	RG	WD	NS
MS	BS		Interacting	
RG			Binaries	
WD				
NS				GRB

We consider now when stars are most likely to be involved in collisions. One may integrate the collision rate equation over the entire lifetime of a cluster to calculate the expected number of collisions n_{coll} for a particular star:

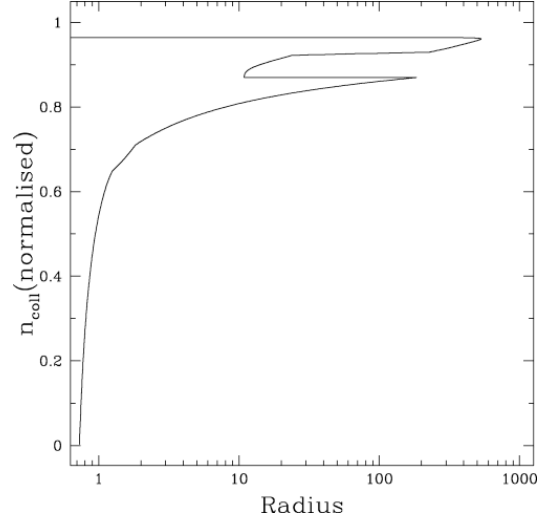
$$n_{\text{coll}}(t) = \int_0^t \Gamma_{\text{coll}} dt = n \int_0^t \sigma(R_*) V_{\infty} dt, \quad (9.3)$$

where Γ_{coll} is the collision rate for the star and $\sigma(R_*)$ is the collision cross section (as given in Eq. (1) with the minimum distance R_{min} set to the stellar radius R_*) which will change as a function of time as the star evolves (and its radius changes).

The number density of stars in a cluster n is assumed to be constant throughout the evolution of the star. The result of such a calculation is shown in Fig. 9.2, where we plot the normalised expected number of collisions as a function of stellar radius for $0.4 M_{\odot}$ stars in a globular cluster (stellar radius is used here as it easily shows the various phases of stellar evolution). The frequency of collisions when the star is large are somewhat reduced because of the effects of gravitational focussing as the cross section $\sigma(R_*) \propto R_*$ rather than R_*^2 . From Fig. 9.2, we can see that some 60 – 70% of collisions will occur whilst the star is on the main sequence, a further 20% or so occur whilst the star is ascending the giant branch, 10% whilst the star is on the horizontal branch and a little less than 10% on the asymptotic giant branch. We thus conclude that the majority of collisions will occur whilst the star is on the main sequence.

We consider now the immediate outcomes of collisions between two main sequence stars. Such collisions are complex events. Understanding them well requires fully 3D computational hydrodynamic simulations. Much work has been done modelling such collisions, particularly involving low-mass main sequence stars with

Fig. 9.2 The cumulative number of collisions as a function of stellar radius (in solar units) for $0.4 M_{\odot}$ mass stars in a globular cluster. The expected number of collisions has been normalised so that the total number of collisions over the entire cluster lifetime is one. The various phases of stellar evolution are clear from this plot: the main sequence phase ending when the stellar radius is few solar radii, the red giant phase extending up to a radius $\sim 200 R_{\odot}$, the star has a radius $\sim 10 - 20 R_{\odot}$ on the horizontal branch, then expands again to over $300 R_{\odot}$ on the asymptotic giant branch. The results obtained for 0.6 and $0.8 M_{\odot}$ models are very similar. (Figure 1 from [34], reproduced with permission)



relatively-low velocities, which are relevant for the encounters of interest to us in globular clusters (including [2, 23, 24, 25, 35]).

There are two speeds to consider in a stellar collision: the relative speed of the two stars at infinity V_{∞} and the surface escape speeds of the stars ($V_{\text{esc}} = \sqrt{2GM_{\star}/R_{\star}}$). For globular clusters, $V_{\infty} \simeq 10$ km/s. In comparison, for low-mass main sequence stars, $V_{\text{esc}} \simeq 600$ km/s. We should not be surprised therefore to find that collisions in globular clusters lead to mergers having little mass loss (typically 1–10 % of mass is lost; e.g., [2, 3]) as the ejection of a small fraction of the total mass can carry off the (small) positive energy contained in the collision.

Snapshots of a typical collision between two low-mass main sequence stars is shown in Fig. 9.3. The stars quickly merge, with little mass loss, although the merged object does contain (unsurprisingly) considerable angular momentum. The post-collision evolution of such a merged object is complex, and will be discussed in the next section.

The energy lost in a head-on impact is equivalent to $\delta V_{\infty} \sim 100$ km/s. Stars will become bound even for close encounters which do not (initially) lead to physical collisions, with the minimum distance to capture $R_{\text{capt}} \sim 3R_{\star}$. Indeed, such a capture mechanism has been invoked as a way to produce the population of low-mass X-ray binaries in globular clusters, where in this case a passing neutron star captures a main sequence star via tidal interactions [12].

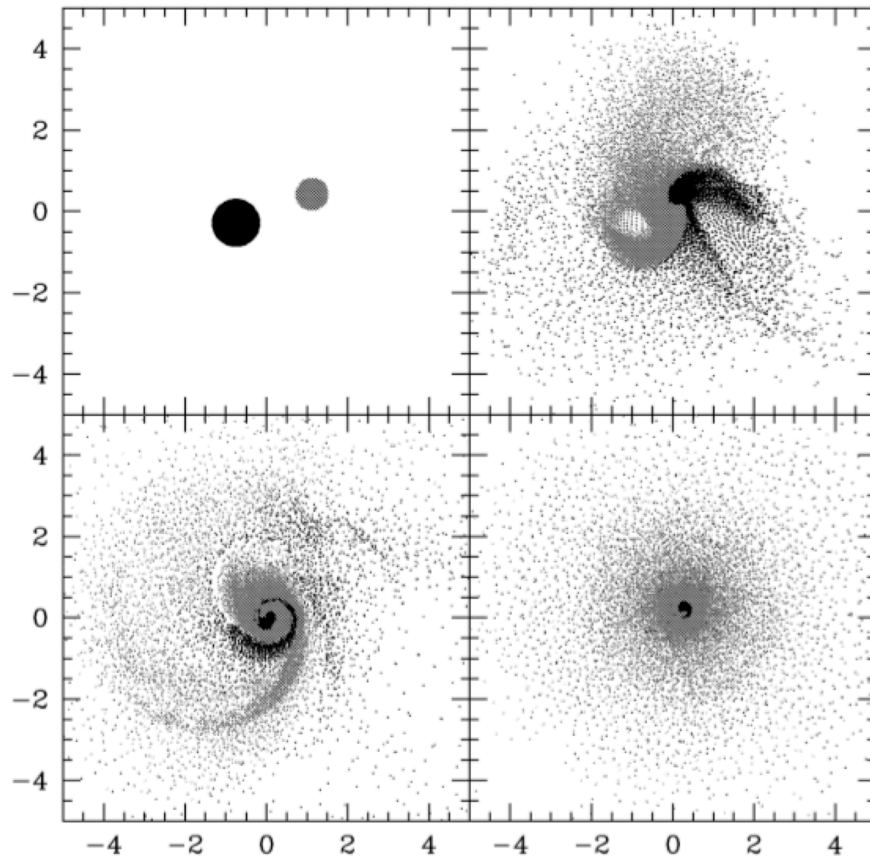


Fig. 9.3 Snapshots of a collision between a $0.6 M_{\odot}$ main sequence star (black dots) and a $0.4 M_{\odot}$ main sequence star (grey dots). The minimum distance between the stars in the initial collision was $0.255 R_{\odot}$, equal to $0.25(R_1 + R_2)$ and the stars had a relative speed at infinity $V_{\infty} = 10$ km/s. The colours represent the density of the gas in the plane of the encounter. (Figure 2 from [34], reproduced with permission).

9.3 Post-collision Evolution

The subsequent evolution of the merger product is complicated, though much modelling work has been done — see, for example, [14, 15, 32, 34, 36, 38, 39].

Even though most of the material is bound in a single merged object, it will not immediately appear as a main sequence star. The incoming kinetic energy of the impact has been converted into thermal energy, the merger product is out of virial equilibrium and will expand.

One is interested to learn about the extent of the expansion and the timescales involved for it to return to the main sequence, if indeed it does so. The object typically

contains significant angular momentum as most collisions are relatively grazing so the merger product contains the angular momentum from the trajectories of the two stars. Indeed many merger products initially contain too much angular momentum to contract down to the main sequence.

By considering angular momentum loss through either disc- or wind-locking, it was shown that both methods allow the merger product to shed sufficient angular momentum to contract down to the main sequence [34].

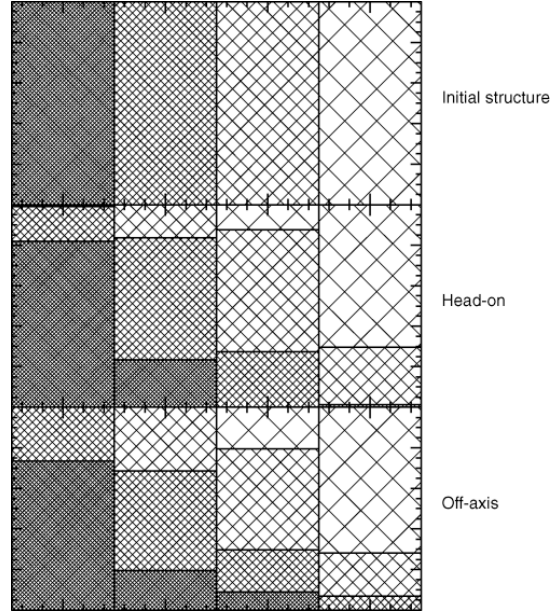


Fig. 9.4 A plot showing the mixing of material which occurs in head-on and off-axis collisions between two low-mass main sequence stars. The four columns in each plot represent four equally-spaced mass bins. (Figure 3 from [34], reproduced with permission)

In modelling the evolution, one is also concerned about how much mixing takes place within the star. Will the core be refueled with a fresh supply of hydrogen to thus extend the life of the blue straggler?

The distribution of matter in low-mass main sequence stars is illustrated in Fig. 9.4 where we show the redistribution of material within the stars as an outcome of both head-on and off-axis collisions [34].

If collisions were to lead to the complete mixing of material, then we would see that the four columns of the initial structure would be completely mixed in the collision products. In other words, the inner mass quartile of the collision product would contain equal amounts of material from each of the four mass quartiles from the initial structure. This is not seen.

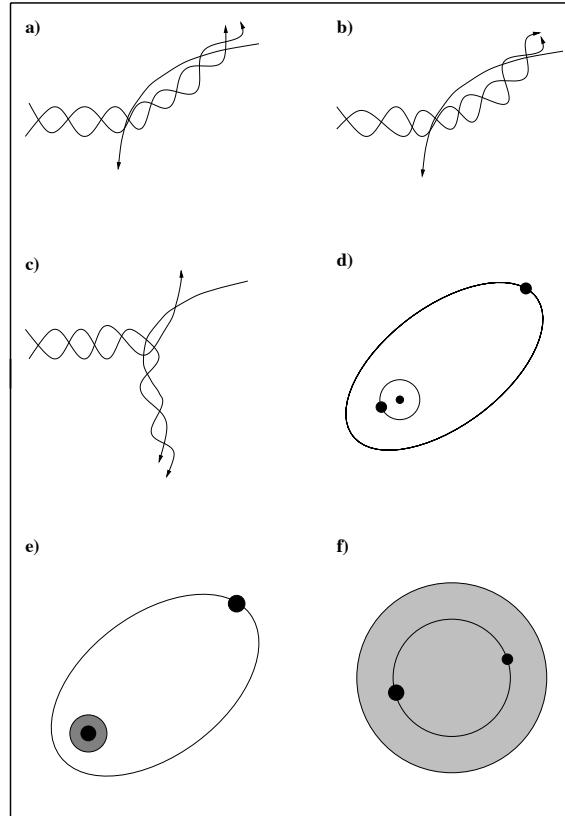
Indeed, only a very small amount of material in the central mass quartile of the collision products is drawn from outer regions of the pre-collision stars (very little mixing is seen also in the work of [32, 39]). Slightly more mixing is seen in off-axis collisions than in head-on collisions (see also [36]).

Mixing is important when one considers the lifetime of the collision product: collisions involving main sequence stars close to the turn-off mass, will contain relatively small amounts of unburned hydrogen in their cores. The lifetime of the collision products will be short unless fresh hydrogen can be brought in to the core of the merger product. Indeed, recent work suggests that blue stragglers have somewhat shorter lifetimes than regular main sequence stars of similar masses [37].

9.4 Encounters Involving Binary Stars

In this section we consider the role played by encounters involving binary stars in producing blue stragglers. Binaries are larger targets than single stars within stellar clusters. Interesting encounters occur when a star passes within a distance roughly equal to the size of the binary. Hence, the time scale for encounters is given by

Fig. 9.5 Possible outcomes of encounters between a binary and a single star: a) a fly-by occurs where the binary's orbit is changed, b) the fly-by leads to the merger of the two stars in the binary, c) the intruding star exchanges into the binary, d) the system forms a (transient) triple system, e) two of the stars merge and remain bound to the third star, and f) a common envelope system is formed where two of the stars orbit inside a gaseous envelope made from the third star.



$$\tau_{2+1} \simeq 10^{11} \text{yr} \left(\frac{10^5 \text{pc}^{-3}}{n} \right) \left(\frac{V_\infty}{10 \text{km/s}} \right) \left(\frac{R_\odot}{a_{\text{bin}}} \right) \left(\frac{M_\odot}{M} \right). \quad (9.4)$$

One can see how encounters between binaries and single stars can be as frequent as encounters between two single stars. For example, if a cluster possesses a binary fraction of around 0.05, then the encounter rates will be similar for binaries of separation $a_{\text{bin}} \sim 60 R_\odot$. There are many outcomes possible for encounters involving binaries as illustrated in Fig. 9.5: fly-bys occur where the binary retains its stellar components although the binding energy and eccentricity of the binary orbit may change; fly-bys may lead to the merger of the two stars within the binary; an intruder star may exchange into the binary with typically the least massive of the three stars being ejected; the system may form a (transient) triple system; two of the stars may merge but remain bound to the third star; or a common envelope system may form where two of the stars orbit inside a gaseous envelope made from the third star.

For us here, considering blue straggler production in stellar clusters, we are particularly interested in the fifth possible outcome, where two stars merge. The outcomes for such mergers are likely to be similar to those seen for collisions between two single stars as described earlier.

We will now consider some general concepts concerning binary-single encounters. If binaries are sufficiently wide, encounters with single stars will tend to break them up as the kinetic energy contained in the incoming star exceeds the binding energy of the binary. Such binaries are referred to in the literature as *soft*. Whereas binaries which are more tightly bound and are thus resilient to break-up are known as *hard*. The separation of the stars in a binary sitting on the hard-soft boundary depends on the masses of the stars in the binary, and the mass of the incoming star. Assuming that all stars are of one solar mass, the binary separation for a system on the hard-soft boundary is given approximately by $a_{\text{hs}} \simeq 6 \text{AU} (V_\infty / 10 \text{kms}^{-1})^{-2}$. Encounters tend to break up soft binaries, whereas hard binaries get harder (i.e. more bound). They are also left with a thermal distribution of eccentricities, where the distribution follows $dn/de = 2e$. As stated earlier, in exchange encounters it is most often the least massive of the three stars which is ejected.

Thus, encounters involving binaries will tend to increase the mass of the stellar components within binaries; a fact which will become important later in this chapter when we compare the blue straggler formation rates in clusters produced from the evolution of primordial binaries to the rate due to collisions and mergers.

The fraction of binary-single encounters which lead to collisions between stars is a function of the binary separation. For binaries having separations around 1 AU, the fraction of strong binary-single encounters where two stars pass within some distance r_{min} is found, through numerical experimentation, to be $f \propto (r_{\text{min}}/a_{\text{bin}})^\gamma$ where $\gamma \simeq 1/2$ [6, 7]. So, for example, collisions and mergers occur in 10-20 % of encounters involving solar-like stars and a binary of separation 1 AU. Thus stellar mergers occurring during a binary-single encounter may make a significant contribution to the total merger rate within a stellar cluster providing the binary fraction is large. In typical globular clusters, where the binary fraction is perhaps around 10

% or smaller (e.g., [28]), the collision rate derived from single-single collisions is likely to exceed that derived from encounters involving binaries.

We now consider encounters involving *two* binaries. The cross section for some kind of strong interaction for binary-binary encounters is in fact roughly the same as for binary-single encounters: we require that the binaries pass within a distance roughly comparable to the size of the binaries. However the fraction of strong encounters leading to physical collisions is larger. This can be seen simply by reflecting that when we have four bodies (i.e. two binaries) involved in a complex encounter the number of distinct pairs $n_4 = 4(4-1)/2 = 6$ whereas for three bodies (i.e. a binary and a single star), the number of pairs is $n_3 = 3(3-1)/2 = 3$.

Thus, we have a much greater chance that at least one pair will suffer a close passage during the whole encounter. Typically a binary-binary encounter quickly

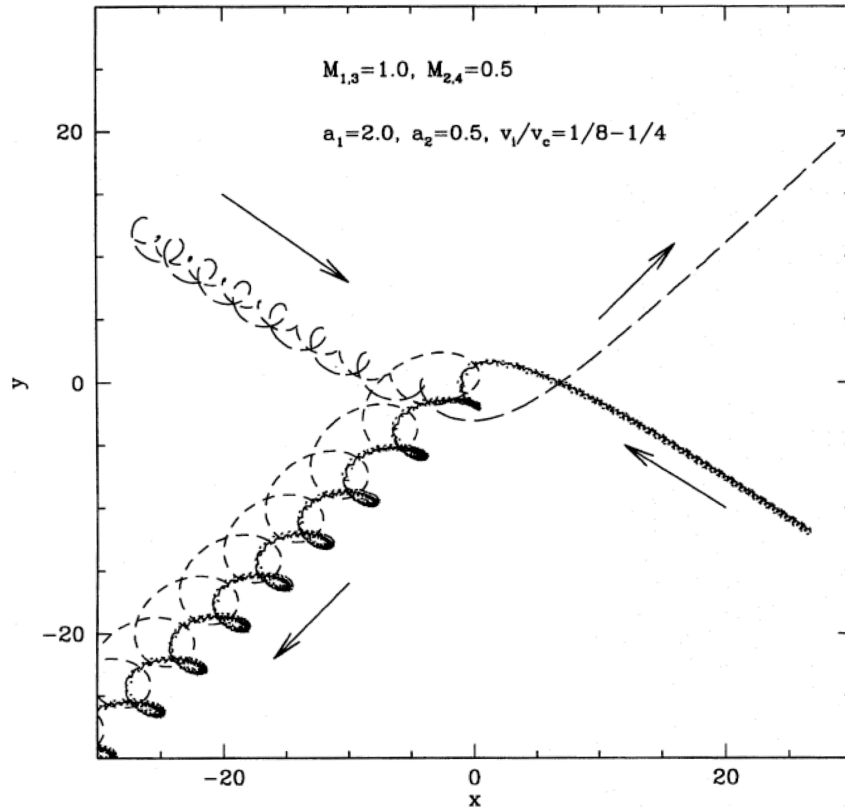


Fig. 9.6 An example of a binary-binary encounter, in this case producing a hierarchical triple and a single star. (Figure 3 from [1], reproduced with permission)

resolves itself into a (transient or stable) triple and a single star. Such an encounter is shown in Fig. 9.6.

In sparse clusters, with lower number densities of stars, collisions between two single stars may be rare. In such cases, collisions occurring during the interaction between two binaries may dominate. There are several papers which contain calculations of cross sections for various outcomes (binary break-ups, exchange encounters, and stellar collisions): including [1, 6, 7, 16, 17, 19, 22, 33].

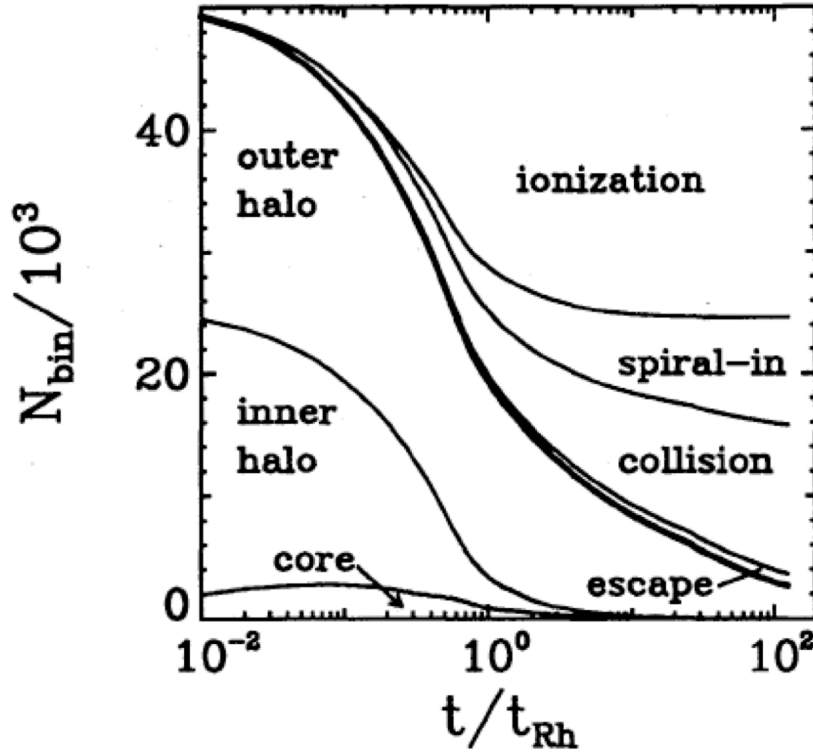


Fig. 9.7 The location and fate of binaries within a stellar cluster, containing initially fifty thousand binaries. The left-hand side of the figure shows the location of any surviving binaries as a function of time (in units of the half-mass relaxation time). The right-hand side of the figure shows the fate of those binaries which have not survived: break-up (ionisation), stars merging (spiral-in and collision), and those (few) escaping from the cluster. (Figure 3 from [18], reproduced with permission)

Binaries are, in many ways, a fossil fuel of globular clusters. Through close encounters with single stars or other binaries, they are broken up or ground down, processed, and sometimes ejected from clusters. Those not formed in clusters' cores

will sink into the core (as they are heavier than the average star) and there undergo close encounters. The fate of binaries within a cluster is shown in Fig. 9.7, taken from [18], who used a simple model to follow a population of primordial binaries within a cluster, allowing them to sink into the cluster core, suffer encounters, be ejected from the core, or the entire cluster. They found that about half of the binaries will be broken up (often termed “ionisation”) — in fact often by encounters with other binaries. Others will be involved in collisions or would be hardened to the point where the two stars in the binary would merge. A very small fraction will escape from the cluster.

9.5 Making Blue Stragglers Via Binary Evolution

In this section we consider the formation of blue stragglers through the evolution of stellar binaries, where either the two stars spiral together and merge as angular momentum is lost via stellar winds, or where mass transfer occurs from one (evolved) star to the other. Both processes may produce stars more massive than the current turn-off, providing in the first case the total mass of the two stars exceeds the current turn-off, and in the second case providing the mass transferred from the primary to the secondary increases the mass of the secondary above that of the turn-off mass of the cluster.

Tight binaries, where the separation is only a few times larger than main sequence stars, may merge as angular momentum is lost via stellar winds [42]. The subsequent evolution of the merger product is likely to be rather similar to that described earlier for objects produced via stellar collisions. Here, as before, the object is likely to be spinning rapidly, perhaps leading to global circulation within the merged object which may help refuel the core with unburnt hydrogen. Clearly the merger product will be a single star, unless the tight binary is itself a component of a wider binary (see [29] and Chap. 11).

We consider now the evolution of binaries which are too wide to merge via angular momentum loss from stellar winds. In such systems, mass may flow from the primary to the secondary star when the former evolves off the main sequence, expanding up the giant branch and filling its so-called Roche lobe where material at the primary’s surface flows toward the secondary star [27]. This mass transfer may be stable, in the sense that the mass transfer rate does not grow rapidly, and the system evolves steadily as the primary evolves up the giant branch (as illustrated schematically in Fig. 9.8). In such a case, the secondary will gain mass from the primary.

Alternatively, the mass transfer can be unstable: the rate increases to the point where a very rapid mass transfer occurs with a large fraction of the primary’s envelope engulfing the secondary forming what is known as a common envelope system where the core of the primary and the secondary star orbit inside this envelope of gas. In this case, the core of the primary and the secondary star will spiral together,

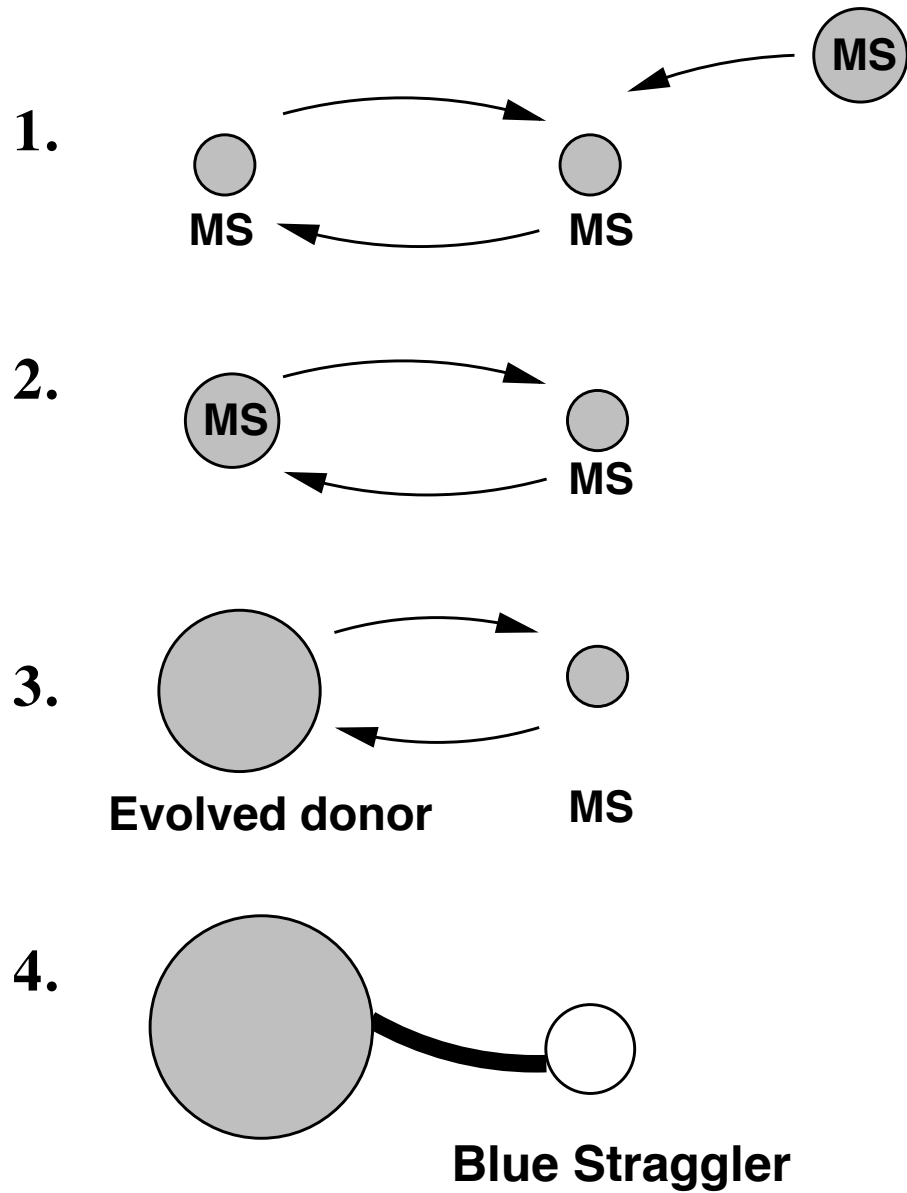


Fig. 9.8 The evolutionary pathway to produce blue straggler stars (BSSs) through mass transfer in wide binaries in globular clusters. A more massive main sequence star exchanges into a binary containing two main sequence stars (phase 1). The typical primary mass after encounters in a sufficiently crowded cluster is $M_1 \simeq 1.5 - 3M_{\odot}$ [8]. This primary evolves off the main sequence and fills its Roche lobe (phase 3). The secondary gains mass from the primary becoming a BSS (phase 4) at a time roughly equal to the main sequence lifetime of the donor star. Hence BSSs have formed earlier in binaries containing more-massive primaries (i.e. in high collision rate clusters). Given the finite lifetime of BSSs, the BSS population in the most crowded clusters today could be lower than in very sparse clusters. (Figure 4 from [9], reproduced with permission).

dumping energy and angular momentum into the surrounding envelope which will be ejected.

In order to compute whether mass transfer is unstable, one has to consider the response of the donor star to its mass loss and compare this to how the size of the Roche lobe changes as mass is transferred (see Chap. 8 for a more detailed discussion). Mass transfer will be unstable when the ratio of the donor radius to the Roche lobe radius increases, in other words, when the star overfills its Roche lobe by increasing amounts.

If the mass transfer is *conservative*, meaning that mass transfers from one star to the other without any loss of material (or angular momentum) via stellar winds, then the separation of a binary will increase if the donor is less-massive than the receiving star, and decrease if the donor is more-massive than the receiving star. One can see that systems containing more massive donors will often be unstable, as once filling their Roche lobes, the donors will overflow their Roche lobes more and more, leading to extremely high rates of mass transfer.

By definition, in the case considered here, the donor is the primary in the binary and will thus be more massive than the secondary (mass-receiving) star. However,

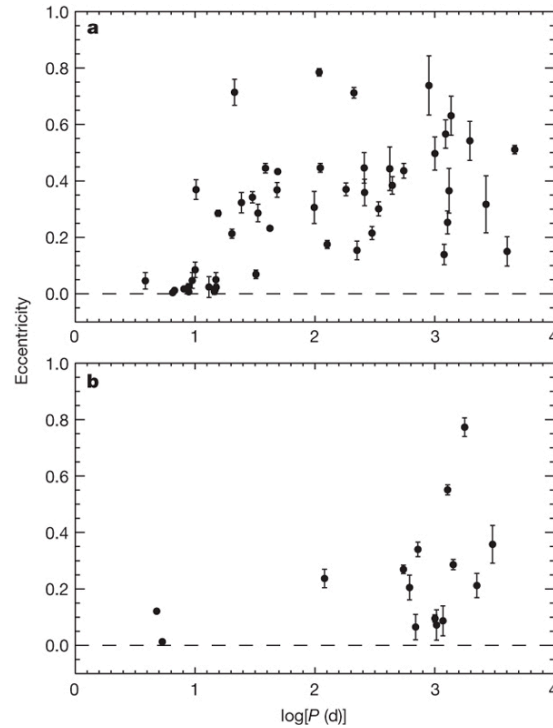


Fig. 9.9 Distribution of solar-type main sequence binaries seen in the open cluster NGC 188 (upper figure), and the binary population for blue stragglers in NGC 188 (lower figure). (Figure 2 from MG09, reproduced with permission)

for systems with an initial mass ratio close to unity, it could be that in some systems an initial phase of mass transfer could change the mass ratio such that the donor is now the less massive star in the binary. What follows is then a phase of stable mass transfer where the envelope of the primary is slowly transferred to the secondary star (on stellar evolutionary timescales) whilst the separation of the binary increases.

Providing mass transfer occurs on the giant branch, one would expect to see at the end of this mass transfer a rejuvenated secondary star (now the more massive star in the system) orbiting around some form of white dwarf (the former core of the primary). The binary separation being a few times larger than red giant radii.

In Fig. 9.9¹ we plot the binary properties of both solar-type main sequence stars and blue stragglers observed in the open cluster NGC 188 ([26]; see also Chap. 3). Interestingly, the vast majority of the blue stragglers are in relatively *wide* binaries. This strongly suggests that these systems have passed through a period of stable mass transfer from a star evolving up the red-giant branch as described above. This is also consistent with the observations in the field that blue stragglers are in wide binaries [4, 31, 40].

9.6 Comparing Primordial and Collisional Formation Rates in Clusters

We may compute how the blue straggler production rate scales with cluster mass, assuming all blue stragglers are made via the two-body collisions described above, and that these collisions occur exclusively within the dense core.

The stellar collision rate within the cluster core is given by $\Gamma_{\text{coll}} \propto \rho^2 r_c^3 / \sigma$, where ρ is the mass density of stars within the cluster core, r_c is the core radius, and σ is the velocity dispersion of the stars which is $\propto \sqrt{M_{\text{tot}}/r_h}$, where M_{tot} is the cluster total mass and r_h is the radius containing half of the cluster's total mass. Also the cluster's core mass $M_c \propto \rho r_c^3$. Hence we have

$$\Gamma_{\text{coll}} \propto \frac{\rho^2 r_c^3}{\sigma} \propto \frac{\rho^2 r_c^3}{\sqrt{M_{\text{tot}}/r_h}} \propto \frac{M_c^2 r_c^{-3}}{\sqrt{M_{\text{tot}}/r_h}} \propto \frac{f_c^2 r_h^{1/2}}{r_c^3} M_{\text{tot}}^{3/2}, \quad (9.5)$$

where $f_c = M_c/M_{\text{tot}}$. Assuming for simplicity f_c , r_c , and r_h are the same for all clusters, we see that $\Gamma_{\text{coll}} \propto M_{\text{tot}}^{1.5}$. Clearly f_c , r_c , and r_h all vary between clusters, though this simply produces a spread around the relationship. In other words, if all the blue stragglers in globular clusters really were produced via two-body collisions, then we would expect to see that the number of blue stragglers increases with cluster mass as

$$N_{\text{bs,coll}} \propto M_{\text{tot}}^{1.5}, \quad (9.6)$$

¹ This is a repetition of Fig. 3.2, reproduced here for the convenience of the reader.

This is not seen in the observed systems as illustrated in Fig. 9.10 where we see that the number of blue stragglers is relatively independent of cluster mass (see also [30]).

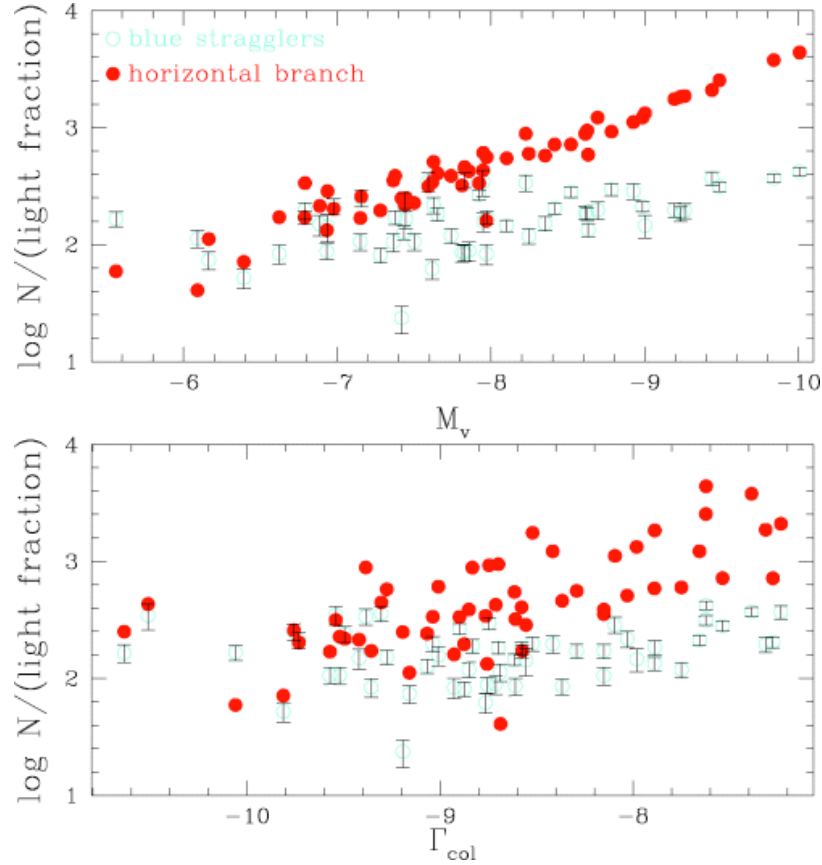


Fig. 9.10 The estimated total number of blue stragglers and horizontal branch stars in the sample of 56 globular clusters as a function of cluster total magnitude M_V (top panel) and stellar collision rate (bottom panel). See [30] for more details. (Figure 1 from [9], reproduced with permission)

We consider now the production of blue stragglers via binary evolution, either through the merger of the two components of a binary, or via mass transfer from the primary to the secondary as the primary evolves off the main sequence. In order for such a process to produce the blue stragglers we see today, the mass of the merger product, or mass transfer enhanced secondary, must exceed the current turn-off mass. The merger or mass transfer event must also have occurred relatively recently, i.e. less than the blue straggler lifetime ago. If we assume here that the merger or mass transfer is driven by the evolution of the primary off the main se-

quence, then this is equivalent to requiring that the primary mass subtracted by the current cluster turn-off mass is less than some amount. For example, if we take a blue straggler lifetime of one gigayear, and a turn-off mass today of $0.8 M_{\odot}$, then we require that the primary mass is in the range $0.8 M_{\odot} \leq M_1 \leq 0.816 M_{\odot}$. We note that this is a rather narrow range of masses (due to the very strong mass dependence of main sequence lifetimes). Typically, only a small fraction of binaries will satisfy this condition. If we consider a binary population where stars are drawn from a reasonable Initial Mass Function (IMF; in our case, from [11]), then we find that the fraction of binaries making a blue straggler seen today would be $f_{bs} \simeq 0.006$. If the binaries which produce blue stragglers are allowed to evolve in globular clusters without any interactions with other stars, then we would simply expect that the number of blue stragglers derived from these primordial binaries would be proportional to the cluster mass:

$$N_{bs,bin} \propto f_{bs,bin} M_{tot} \quad (9.7)$$

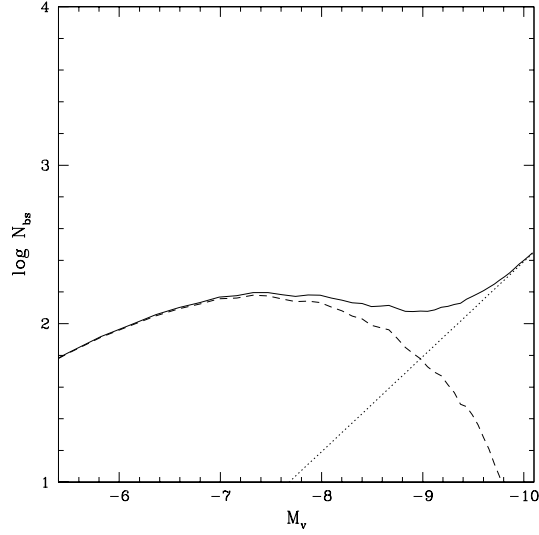
where $f_{bs,bin}$ is the fraction of the original binary population contributing to the blue straggler population today, i.e. those with primaries in the mass range $0.8 M_{\odot} \leq M_1 \leq 0.816 M_{\odot}$.

Let us assume that the two mechanisms described above are the only two contributing to the observed blue straggler population seen in globular clusters. How could their combination produce a population which is relatively independent of cluster mass, given the mass dependencies described in Eq. (9.6) and (9.7)?

The key point here is that dynamical interactions occurring within the stellar cluster which will alter the binary population: 1) exchange encounters with single stars occur where less-massive stars in binaries are replaced by more-massive single stars; 2) stellar collisions may occur during binary-single encounters (see Figure 9.5) which lead to mergers and may remove the binary from the population; 3) some binaries may be destroyed by binary-binary encounters.

Thus in more massive clusters, the binaries will on average have experienced more close encounters with single stars and binaries. Binary-single encounters scale with cluster mass in the same way as two-body collisions seen in equation (9.6). From exchange encounters, the binaries will tend to contain more massive stars today. This will *reduce* the fraction of binaries contributing to the blue straggler population today, as more of the primaries in the binaries will have evolved off the main sequence too long ago in the past: the blue stragglers they produced have been and gone by today [9]. However, as pointed out by Knigge (private communication; see also Chap. 13), stellar evolution may reduce this effect as stars will have evolved, becoming (less-massive) compact remnants before they encounter binaries. If the binaries are in mass-segregated stellar cluster cores, more of the stars they encounter will be massive and thus more massive stars will exchange into binaries before they evolve. Even if this effect is limited, binary destruction via stellar collisions and binary-binary encounters may be equally effective in reducing the blue-straggler population derived from binaries. The destruction of binaries via these two mechanisms is shown in Figure 9.7 (see also [18]). Observational evidence for lower

Fig. 9.11 The number of BSSs produced over the last Gyr as a function of absolute cluster luminosity, M_V , assuming $M/L_V = 3$ for all clusters. The contribution from primordial systems is shown with a dashed line, whilst those produced via collisions (involving either two single stars or binaries) is shown as a dotted line. The total is given as a solid line. (Figure 6 from [9], reproduced with permission)



binary fractions in more massive clusters (and thus, on average those having more dynamical interactions) has been reported by [28].

Combining the contribution from stellar collisions and that from binaries, we have

$$N_{bs} = k_{bs,coll} M_{tot}^{3/2} + k_{bs,bin} f_{bs,bin}(M_{tot}) M_{tot} , \quad (9.8)$$

where $k_{bs,coll}$ and $k_{bs,bin}$ are suitably chosen constants. $f_{bs,bin}(M_{tot})$ has been determined through Monte Carlo calculations of binary-single encounters including only the effects of exchange encounters, not including the effects of stellar evolution [9].

The number of blue stragglers expected as a function of absolute cluster magnitude is shown in Fig. 9.11. Here we have assumed a mass-to-light ratio $M/L_V = 3$, and have taken reasonable values for the two constants (see [9]). Including the effects of stellar evolution could reduce the effect due to exchanges, but the binary population will also be reduced via stellar collisions during binary-single encounters and by binary destruction during binary-binary encounters. The net effect is likely to be the same: in environments where interactions with other stars and binaries are sufficiently frequent, the contribution to the blue straggler population made by binaries is reduced. We see that the blue straggler population derived from binaries dominates for most clusters and that direct collisions only become important for clusters brighter than $M_V = -9$ (or equivalently a mass, $M_{tot} = 10^6 M_\odot$). Indeed, by considering the number of blue stragglers found in cluster cores and comparing this to the total stellar mass contained in cluster cores, Knigge et al. [20] concluded that most blue stragglers come from binary systems — but see also [21].

It is important to recall that the trend shown in Fig. 9.11 has been derived assuming average cluster properties (the dependence on cluster mass given in Eq. (9.6)

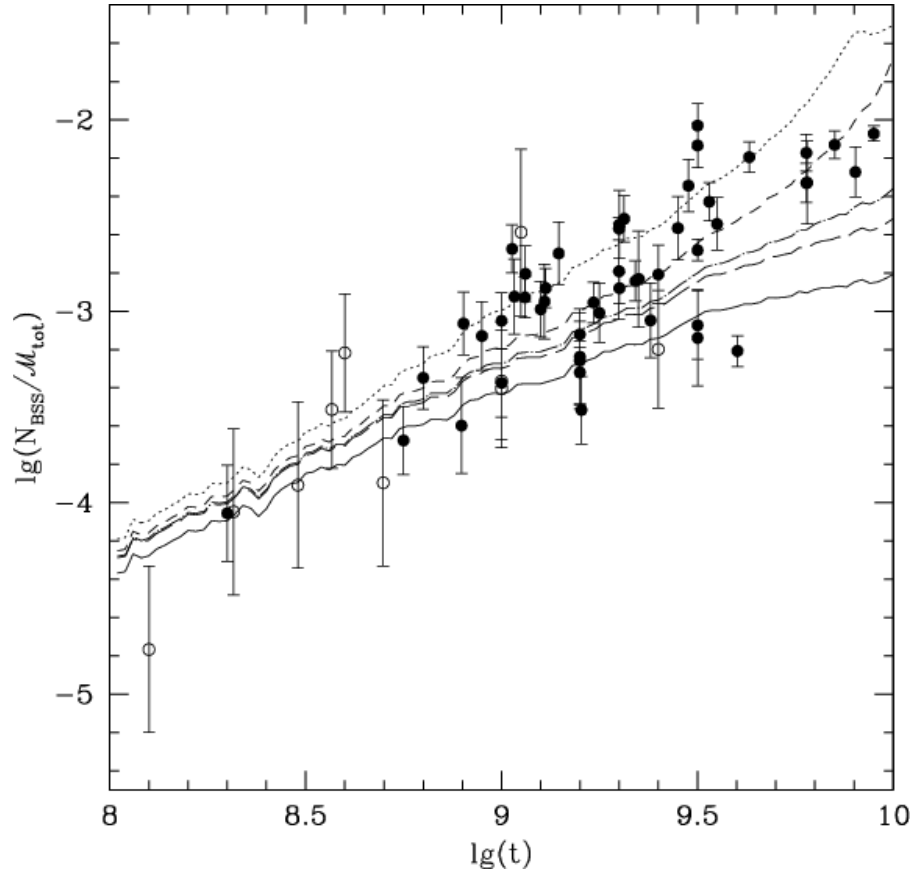


Fig. 9.12 Comparison between the expected number of blue stragglers and the number observed in open clusters. The solid line represents the model given in [10] where it is assumed that the observed blue stragglers are derived from primordial binaries which have undergone mass-transfer. Dotted, dashed, dot-dashed and long-dashed curves reproduce respectively the expected values obtained taking into account the evaporation of stars from clusters following the models of [41] with 2k, 8k, 32k, and 131k N-body models. (Figure 8 from [10], reproduced with permission)

assumed for example that all clusters have the same core and half-mass radii). There will be outliers to the distribution shown here. Nonetheless, the turn over in the blue straggler population derived from primordial binaries seen here due to encounters with single stars (and perhaps also binary destruction through stellar collisions and binary-binary encounters) does explain the observed, relatively flat, blue straggler population. There is observational evidence that two formation channels for blue stragglers occur in at least one globular cluster — M30 — as two distinct blue-straggler sequences have been observed [13].

It should also be noted that the *specific* frequency of blue stragglers seen in clusters (i.e. the number per unit mass) is in fact *less* than one would obtain for binaries in the field. This is because binary-single encounters (and binary-binary encounters) act to reduce the fraction of binaries contributing to the blue straggler population today. Thus the largest specific frequency of blue stragglers derived from binaries will occur in low-density environments where no such encounters are expected: in the low-density haloes of clusters and in field of the Galaxy. Indeed, this is consistent with observations of blue stragglers seen in the Galactic halo [4, 31, 40] and also in open clusters, where the observed population follows that expected if it is derived from primordial binaries which have undergone mass transfer, as shown in Fig. 9.12 [10].

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